Application of Airdrop Systems Modeling Software

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A modular framework has been developed that permits a standardized integration of numerical simulation software and experimental data relevant to airdrop and aerial delivery operations. The software, called the Simulation Control Module (*SCM*), has been developed to coordinate the operation of separate analysis modules required to simulate the multi-component physics of fluid-structure interaction (FSI) problems. The *SCM* provides a mechanism with which to couple and connect different analysis modules in different ways. This new flexibility allows different flow and structural solvers to be mixed and matched according to user preference. A series of benchmark problems, based upon previously published cases, have been formalized in order to allow the verification of the accuracy and performance of candidate analysis software. This test suite consists of the following: a flat circular disk; a simplified simple rigid canopy; and a coupled FSI simulation of a T-10 canopy.

Nomenclature

C_d	=	drag coefficient
CFD	=	Computational Fluid Dynamics
CHSSI	=	Common High Performance Computing Software Support Initiative
CID	=	Computational Interface Dynamics
CSD	=	Computational Structural Dynamics
CTP	=	Critical Technical Parameter
DSSA	=	Decelerator System Simulation Application
FSI	=	Fluid-Structure Interaction
SCM	=	Simulation Control Module
S	=	Speedup = T_o/T_N
T_o	=	Execution time using *1* processor
T_N	=	Execution time using N processors

I. Introduction

IN order to perform the simulation and modeling of the fluid-structure interaction (FSI) phenomena relevant to airdrop and aerial delivery operations, it is increasingly more important that the analysis software interact in a standardized fashion and be integrable with experimental data. The Airdrop and Aerial Delivery Project, part of the Collaborative Simulation and Test (CST) Portfolio, within the Common High Performance Computing Software Support Initiative (CHSSI), attempts to address these issues. The CHSSI portfolio projects are supported by the US Department of Defense High Performance Computing Modernization Program (HPCMP) Office and are designed to make research-oriented software easier to use by a larger segment of the technical community. In the Airdrop and Aerial Delivery Project the effort started with a coupled analysis code[1] that had been developed under the sponsorship of the U.S. Army Natick Soldier Research, Development, & Engineering Center. The code is referred to here as *FSIBASELINE*. The software was first deconstructed into its component parts. A generic Simulation Control Module (*SCM*) was then developed to coordinate the operation of the corresponding separate analysis modules. A system of library calls was constructed to allow information to be passed between modules via several different mechanisms. Initial work on this project has been documented by Charles *et al.*[2].

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The *SCM*, in conjunction with the integration software also being developed for the portfolio, provides a standardized framework within which to couple and connect different analysis modules in different ways. This new flexibility allows different flow and structural solvers to be mixed and matched more based upon the preference of the modeler and less upon the historical usage of the software modules themselves. Previously the coupling strategy resulted in the analysis modules operating as portions of the same executable code. The new *SCM* approach allows module *executables* to communicate with each other via the *SCM* through a *worker–manager* paradigm. In this model, the worker modules would typically be the modules that perform the Computational Fluid Dynamic (CFD), Computational Structural Dynamics (CSD), or Computational Interface Dynamics (CID) functions within the simulation.

A set of benchmark problems, drawn from previously published cases, have been formalized in order to allow the verification of the accuracy and performance of candidate analysis software. This test suite consists of the following: the canonical bluff body for this application, a flat circular disk; a simplified simple rigid canopy shape; and a coupled FSI simulation of a T-10 canopy. Characteristic coefficients of drag (C_d) for each case are reported. Two further examples are presented, one where the Portfolio integration software is used to produce a series of aerodynamic force coefficients for use as input to an additional modeling tool, and the second where the drag response of a T-10 system is used to explore the design parameter space of the parachute system.

II. Test Cases

Three previously documented test cases were chosen as benchmark applications. A Rigid Circular Disk Case[3] consisted of 209,410 nodes and 1,304,169 tetrahedral elements. A Rigid Canopy Case[4] consisted of 129,970 nodes and 805,797 tetrahedral fluid elements. And finally, a flexible FSI T-10 Canopy Case[5] was made up of 152,558 nodes and 945,202 tetrahedral-shaped fluid elements and a structural model composed of 3385 nodes distributed among 5880 membrane, 1496 cable, and 4 payload (concentrated mass) elements. The computational meshes and representative flow data results are presented in Fig.s 1-3. Uniform flow was imposed upon the left boundary in a direction along the main axis of the flow domain. No-slip velocity conditions were imposed on the object nodes themselves. Slip conditions were imposed along the flow domain surfaces parallel to the main flow direction. These boundary conditions allowed flow in that direction but not normal to the boundary surface. Finally, a stress-free boundary condition was applied to the outlet surface (the surface on the face opposite the inlet surface). Each test case was started impulsively from a rest condition and was allowed to evolve until "steady-state" conditions were asymptotically approached. For the FSI T-10 Canopy Case, the flow was initially allowed to converge around a fixed rigid canopy configuration. The canopy material was then allowed to move and interact with the fluid flowing around it. With the canopy allowed to be mobile, the fluid mesh was also allowed to move each time step during the course of the calculation. Aerodynamic forces and moments were output by the simulation software but the primary result of interest was the coefficient of the drag force (C_d) (the force along the major axis of the computational domains in Fig.s 1-3). For the case of the FSI T-10, the effect of the force of gravity was also taken into consideration along the major axis. In all three cases an initial vortex ring was established around the lip of the disk or canopies (see the second image in Fig.s 1 and 2). After a sufficient evolution time the vortex ring detached and broke apart as it was convected down-stream of the object. A semi-periodic oscillation then developed (see the second image in Fig. 3) that eventually damped down to lower amplitude and slower frequency oscillations around a "steady-state" drag value (see Fig. 4).

An asymptotic value for the C_d of 1.19 was obtained for the Rigid Circular Disk Case that compared well to 1.14 obtained by Johari and Stein[3] and 1.17 by Hoerner[6]. The same computational grid was used in conjunction with a different flow-solver (*Aeolus*) resulting in a C_d value of 1.18. An asymptotic C_d value of 1.50 was obtained for the Rigid Canopy Case. This value which compared favorably to 1.47 reported by Johari Stein, and Tezduyar,[4] and a value of 1.42 from Hoerner[6]. A C_d value of 0.83 was obtained for the FSI T-10 Case. This value also compared favorably to a value of 0.89 determined by Sahu, Edge, Heavey, Stein, and Benney[7] and a range of 0.78 to 0.87 reported by Knacke[8] for this type of parachute. In all cases the values found for the "steady-state" C_d's were within the error variance allowed by the project.

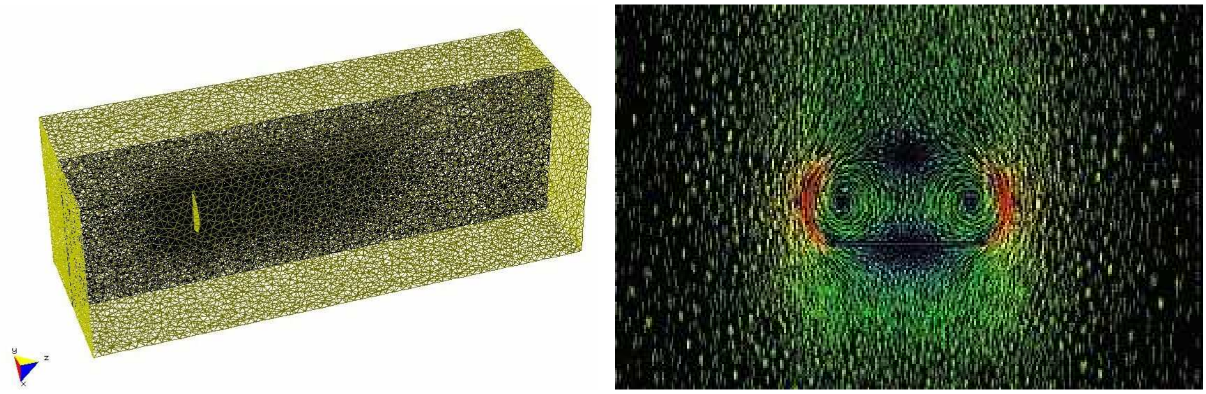

Figure 1. Rigid Circular Disk Case computational geometry and velocity vector pattern results.

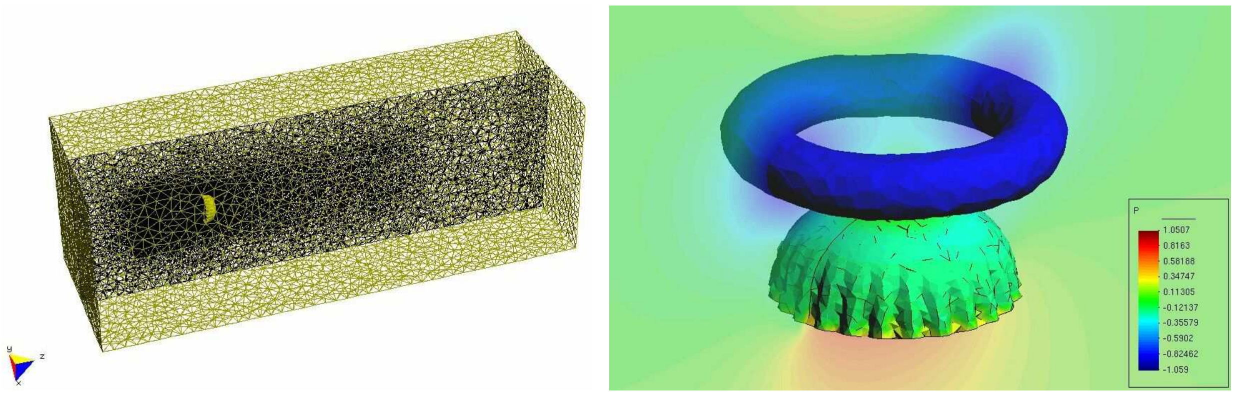

Figure 2. Rigid Canopy Case computational geometry and iso-surfaces colored by pressure results.

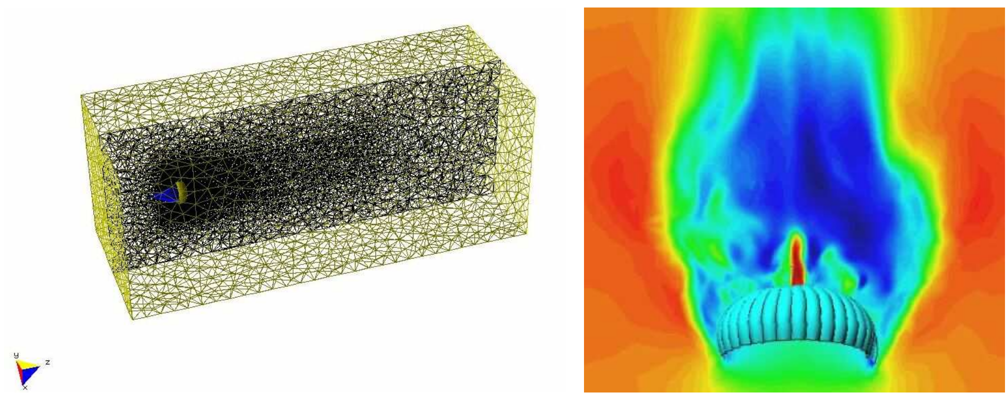

Figure 3. FSI T-10 Canopy Case computational geometry and velocity magnitude contour plot.

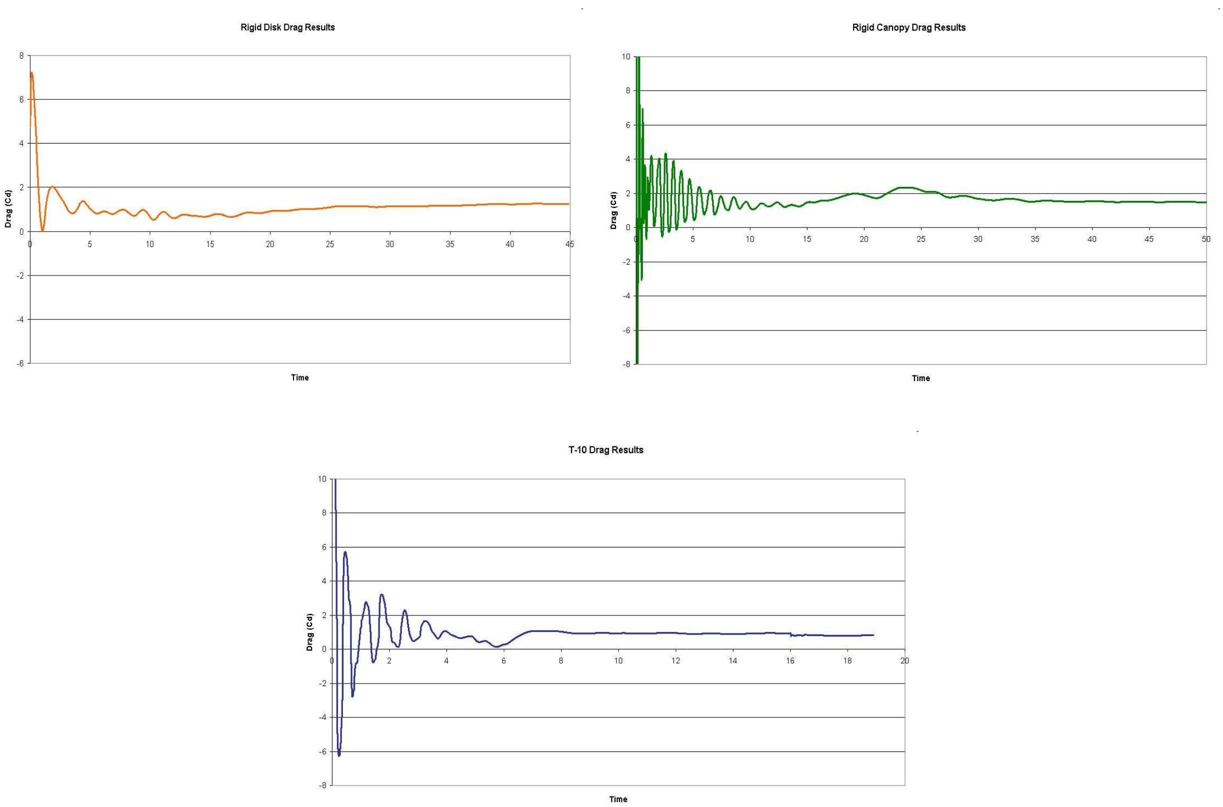

Figure 4. Drag force plots for the Rigid Circular Disk Case, the Rigid Canopy Case, and the FSI T-10 Case.

III. Measuring Performance (CTPs)

For the purposes of the CHSSI program, there were four measures of success referred to as Critical Technical Parameters (*CTPs*): *portability*; *accuracy*; *scalability*; and the successful *integration* of the various simulation modules via the *SCM* mechanism for the project and the successful *integration* of the *SCM*-based analysis code with the Portfolio integration software (STEPNET).

In the course of the project the initial *FSIBASELINE* software was officially *ported* to and run on four different DoD high-performance computing machines: the IBM Netfinity Cluster ("*Huinalu*") at the Maui High Performance Computing Center (MHPC); the IBM Cluster 1600 ("*Kraken*") at the Naval Oceanographic Office (NAVO) Major Shared Resource Center; the SGI Origin 3900 ("*Hpc11*") at Aeronautical Systems Center (ASC) Major Shared Resource Center; and the SGI Altix 3700 ("*Eagle*") also at ASC. Slight modifications to the software were required for each machine to due differences in compilers, libraries, and the way the batch queue systems had to be used. For the final performance test, only the last three machines were considered. For each machine the short- and long-duration operation of the simulation software was tested and the asymptotic results for the C_d values verified, thereby satisfying the *accuracy CTP*.

For each test case, on each of the machines, the *scalability*, *S*, of the software (here defined as the time to run a given problem a given number of time-steps on one processor (T_o) divided by the time to run the same problem on N number of processors (T_N)) was measured out to a value of 64 processors. The theoretically best achievable value of *S* possible is 64 for 64 processors. This corresponds to a line with a slope of 1.00 (often called "linear *speedup*"). For the purposes of the project, the minimum *speedup* acceptable on any of the machines had to be equal or greater to a line with slope of 0.625 (a speedup of 20 for 32 processors or 40 for 64 processors). The results for this *speedup* characterization of the *FSIBASELINE* software on the various machines is presented in Figure 5 where the machine performance data lie above the minimum acceptable red line and below the theoretical maximum black line.

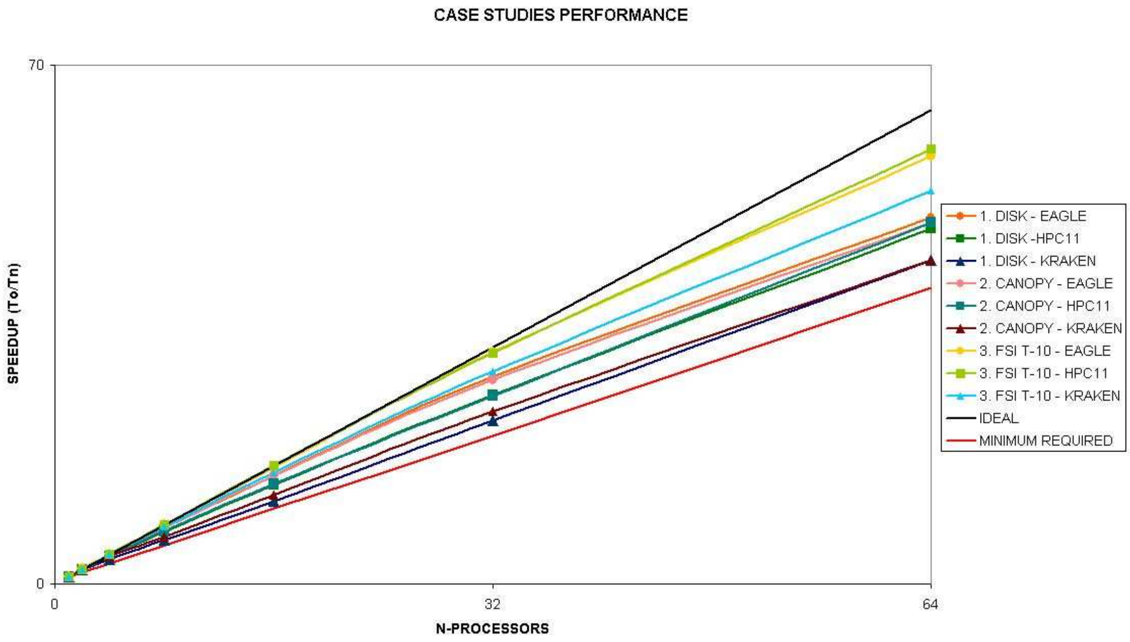

Figure 5. Combined Performance Chart.

IV. Integration

The development of the Simulation Control Module (*SCM*) required starting with the existing FSI analysis code and analyzing its method of operation. Three independent executable modules were then created from this code and the correct points of communication and interaction were identified. Next, the pieces were put back together under control of the *SCM* which shepherded the communication between the different module executables. The typical evolution of the simulation through a standard time-step is shown in Fig. 6. First the response of the canopy structure to the applied loads is calculated. These loads are imposed onto the structure by pressures on the adjacent faces of nearby fluid elements. The fluid mesh is allowed to move in response and a new solution to the fluid system is calculated. The process can then be repeated for the next time-step. During the process, the quality of the fluid mesh is checked as well.

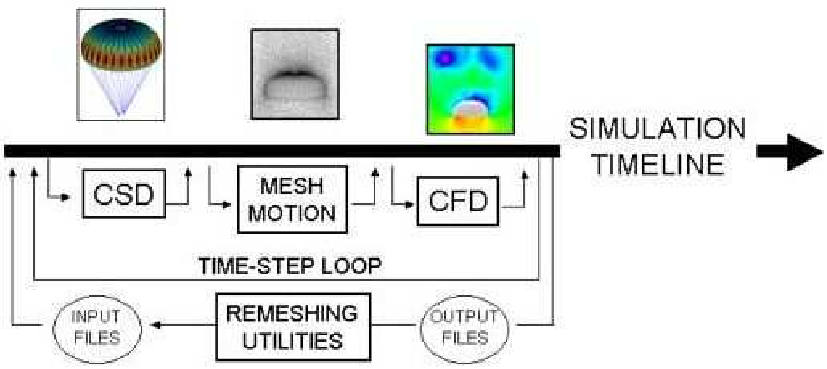

Figure 6. Coupled *FSIBASELINE* sequential iterative solution loop.

Depending upon the operating mode of the *FSIBASELINE* software, the fluid, the solid, or the coupled (both fluid and solid as well as the interface routines) portions of the software can be exercised. The appropriate required files need to be available to the executable code (as shown in Fig. 7). The code is typically run for a set number of time-steps and the output and results are then analyzed. The code can then be restarted and run for another increment of time-steps after first copying the appropriate output files into the corresponding input files for the restart (see Fig. 7).

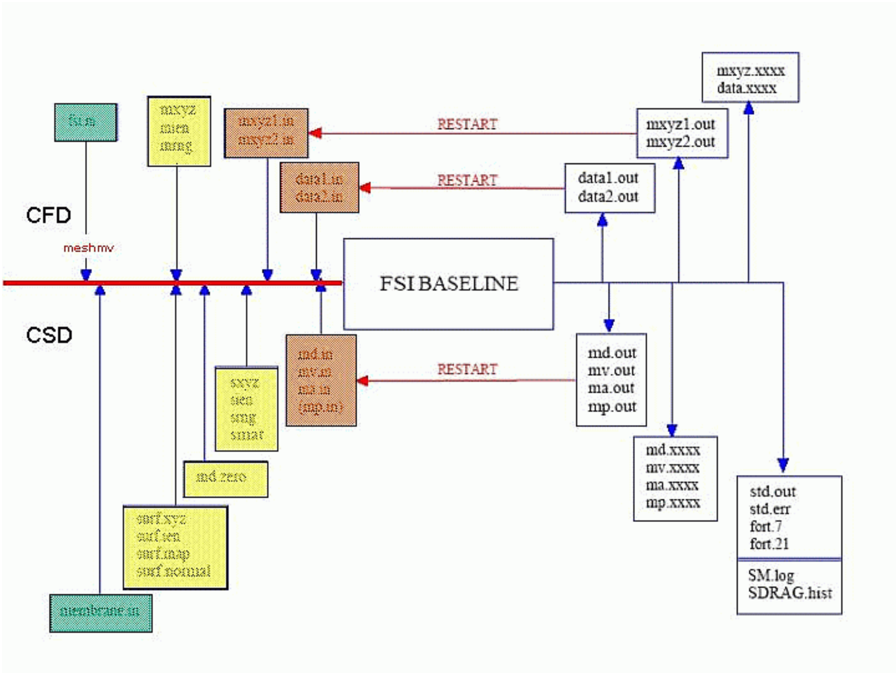

Figure 7. File Interaction.

The first step in designing the *SCM* was to define the nature of interaction between simulation modules in the "*SCM*" and "Worker" model (see Fig. 8). There is always one *SCM* module that is customized for each application that controls the operation and flow of information between simulation modules through "sends" and "receives". (Currently there are three flavors of the *SCM* that use PVM (the Parallel Virtual Machine), MPI (Message Passing Interface), and FIFO (File In – File Out) mechanisms for communicating between a *Worker* and the *SCM* and the *SCM* and a *Worker*. For the application of the *SCM* model to the *FSIBASELINE*, the "*Worker 1*", "*2*", and "*3*" correspond to the CFD, CID, and CSD modules.

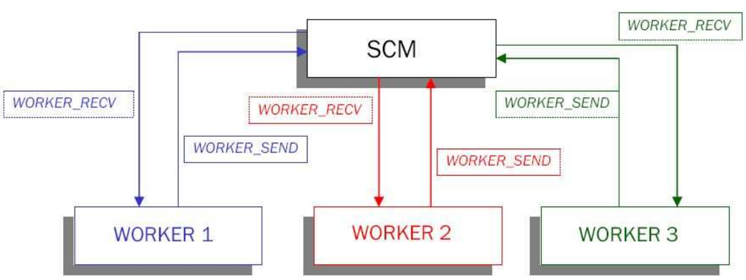

Figure 8. *SCM* coupling strategy.

A detailed analysis of the operation of the *FSIBASELINE* software resulted in the overall operation schematic shown in Fig. 9 and the detailed representation shown in Fig. 10. The horizontal division between the CFD and

CSD modes of operation schematically shown in Fig. 7 corresponds to separating the left column of action in Fig. 9 from the other two columns. Each horizontal transfer between the columns corresponds to communications coordinated through the *SCM*. There are a total of three transfers (two per time-step) between the CFD and CID modules and eight transfers (four per time-step) between the CID and CSD modules. While all three module executables read in required input files only the CFD and CSD modules output result files.

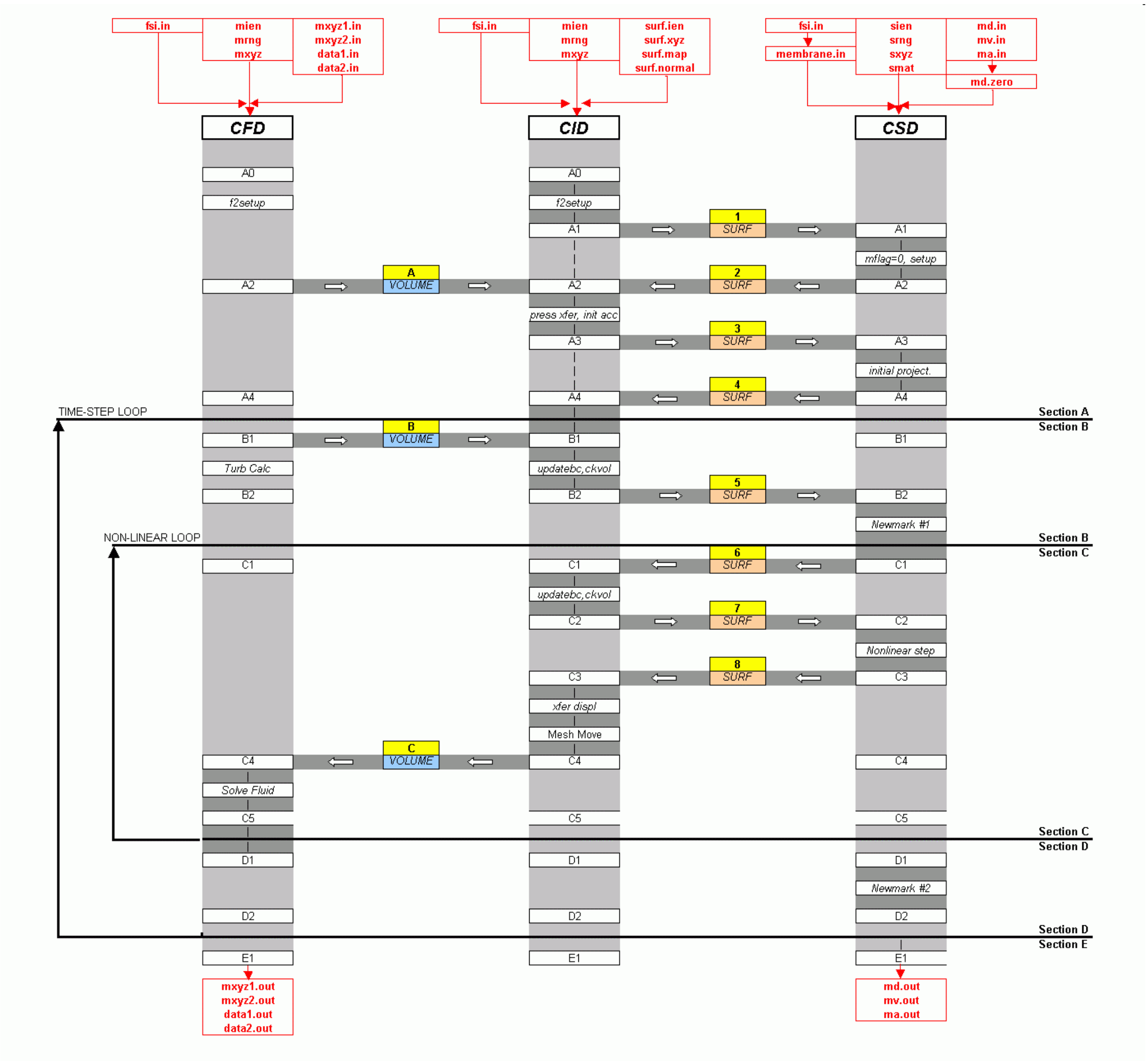

Figure 9. Overall Module interaction.

Focusing on the actions that take place in a given time-step (see Fig. 10), the current fluid volume is transferred by the CFD module to the CID module. The CID module checks the quality of the volume mesh elements and performs updates to the boundary conditions. The CID module transfers the updated interface mesh (the surface mesh corresponding to the membrane elements of the structural model) to the CSD module. The CSD module performs the first part of the Newmark advancement[8,9]. The surface mesh is then transferred back to the CID module where the mesh is then checked and the boundary conditions updated. The surface mesh is then passed back to the CSD module so that the CSD module can perform the nonlinear step advancement. The CSD module then passes the surface mesh back to the CID module where the mesh displacements are imposed upon the fluid volume mesh and the volumetric fluid mesh elements are moved as required. The volumetric fluid mesh is then sent back to the CFD module where a new flow-field solution is obtained. The process is then repeated for a new time-step. The results of the operation of the *FSIBASELINE* code for the FSI T-10 Case were compared to the results obtained by using the *SCM* and the CFD, CID, and CSD modules and the differences were negligible.

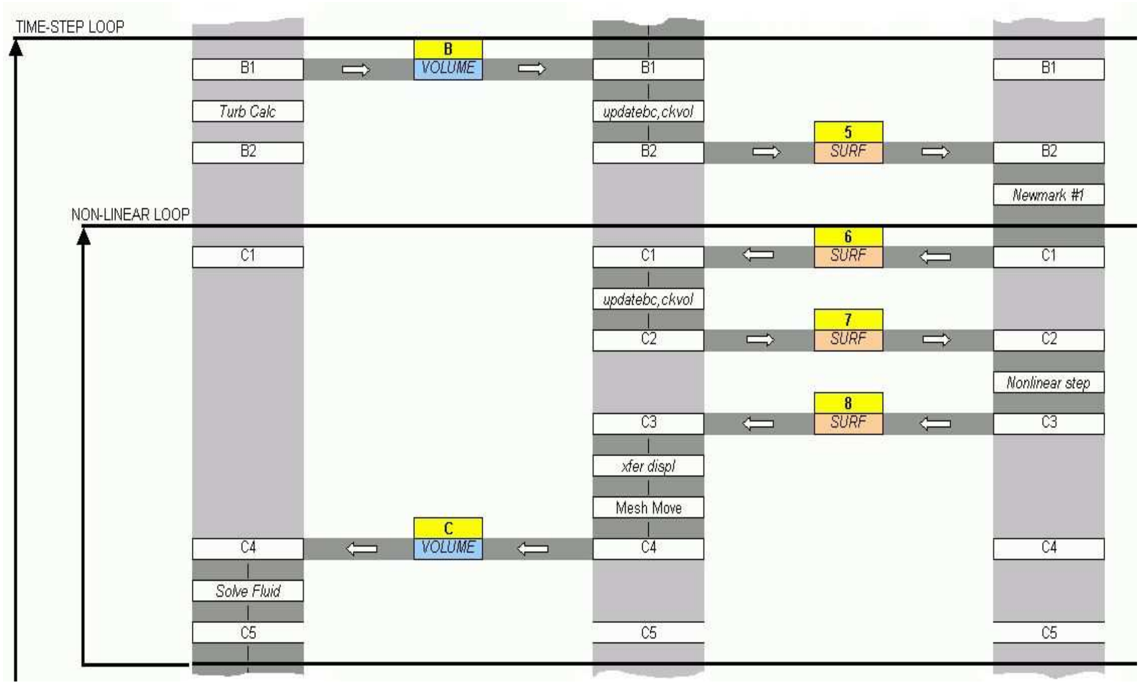

Figure 10. Detailed Communication.

Within the CHSSI Portfolio there was an Integration Project whose objective was to facilitate the way a researcher interacts with simulation codes and experimental data. The goal of this Integration Project, called STEPNET, is shown schematically in Fig. 11. The researcher can interact with archived experimental and simulation results, exercise simulation software on DoD HPC platforms and perform parameter space explorations through a customized user interface that facilitates all of the described activities.

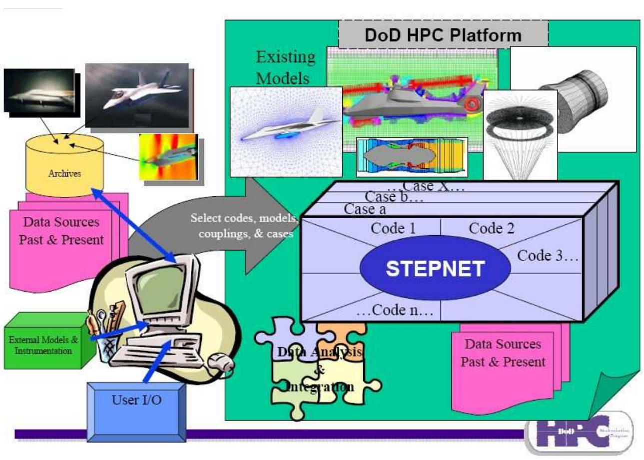

Figure 11. The STEPNET Concept.

V. Present and Future Work

The STEPNET concept was used in the Airdrop and Aerial Delivery Project in two ways. In the first case, a series of CFD runs were performed at the Naval Air Systems Command (NAVAIR) by personnel using the analysis code USM3D (a code being developed under the support of the Vehicle Performance, Stability & Control (Fixed Wing) Project). The runs looked at the effect of a parametric variation of changing the angle of attack of an airstream impinging upon a bluff body of a shape characteristic to Aerial Delivery operations. STEPNET is ideally suited for this type of task. The results of this effort are summarized in Fig. 12 and provided input for improving the modeling capability of a third code, the Decelerator System Simulation Application (DSSA)[10,11], currently being augmented to handle tabulated aerodynamic coefficient input for modeling Aerial Delivery systems[12] .

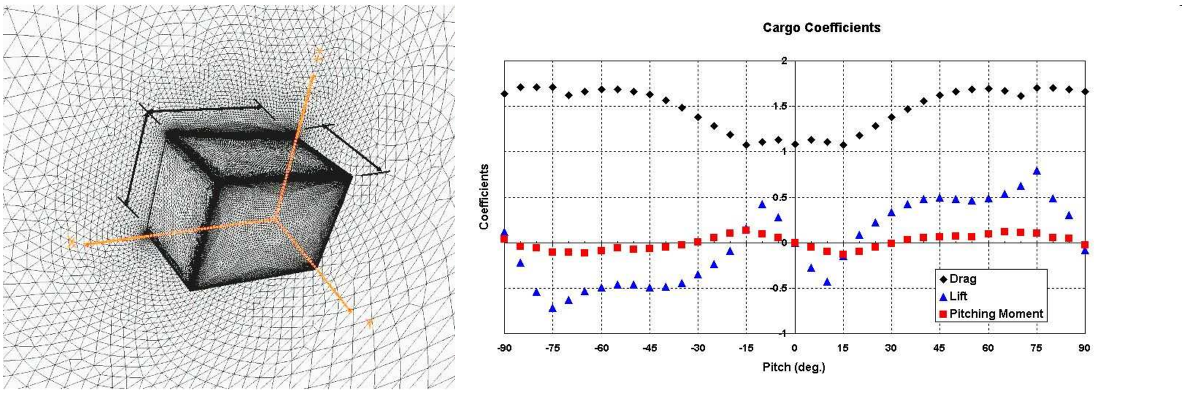

Figure 12. Input to the Decelerator System Simulation Application (DSSA) via the STEPNET Model.

In the second case, the coupled FSI analysis approach was used to look at the effect of varying the Young's Modulus of Elasticity and material thickness of the canopy structure model defined in the FSI T-10 case study. A baseline case was run using the original material properties for 120 time-steps. The nominal value of the Young's Modulus was then doubled and halved for constant values of material thickness. The nominal thickness value was doubled and halved for constant values of Young's Modulus. This resulted in nine different response curves that qualitatively illustrate the ways that parameter space exploration might be used in the design process. The results are given in Fig. 13. In the first image, the thickness was varied from front to back (1/2, 1, and double the original thickness) while the Modulus of Elasticity was allowed to vary as response surfaces (1/2 nominal – blue, nominal – red, double nominal – green). In the second image of Fig. 13, the Young's Modulus was varied from front to back (1/2, 1, and double the original value) while the thickness was allowed to vary as response surfaces (1/2 nominal – blue, nominal – red, double nominal – green). The STEPNET paradigm is well-suited to assisting such explorations of system responses to changes in material property parameters.

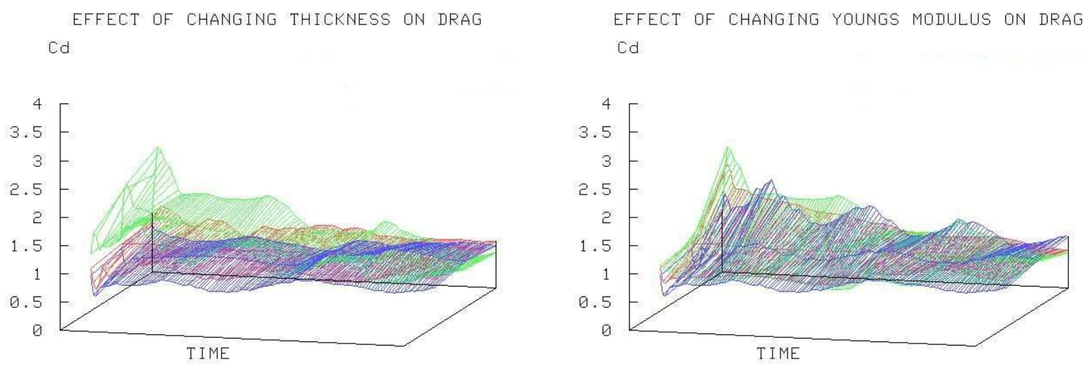

Figure 13. FSI Parameter Space.

VI. Conclusion

There are several ways in which the effort invested in this project is planned to be exploited. First of all, there are efforts currently underway to modify the most recent and capable version of *TENSION*[8,9] (the stand-alone CSD analysis code developed at the University of Connecticut) to be compatible with the *SCM*. Successful completion of this effort will be a great augmentation of the CSD capabilities of the coupled modeling tools. Similar efforts are planned for the CFD code *Aeolus* (a CFD code developed by Dr. Andrew Johnson while at the Army High Performance Computer Research Center (AHPCRC)). In addition, the *SCM* is envisioned to facilitate the use of advanced mesh movement techniques that were also explored within the term of the project. These tools are intended to aid in the modeling of parachute system responses resulting in very large deformations of the structure without the need to totally remesh the fluid volume.

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